The birth place of gamma-ray bursts: abundance gradients and constraints on progenitors

Enrico Ramirez-Ruiz[1], Davide Lazzati[1] and Andrew W. Blain[1,2]

[1]*Institute of Astronomy, Madingley Road, Cambridge, CB3 OHA, England;*
enrico,lazzati@ast.cam.ac.uk
[2]*Department of Astronomy, California Institute of Technology, Pasadena, CA 91125, USA;*
awb@astro.caltech.edu

ABSTRACT

The physics of gamma-ray bursts (GRBs) and their offsets from the centers of their host galaxies are used to investigate the evolutionary state of their progenitors, motivated by the popular idea that GRBs are linked with the cataclysmic collapse of massive stars. We suggest that GRB progenitors in the inner and outer regions of hosts may be intrinsically different: outer bursts appear to have systematically greater isotropic equivalent energies (or narrower jets). This may provide an interesting clue to the nature of GRBs, and could reflect a relation between metallicity and the evolution of GRB progenitors. If true, then this offset–isotropic luminosity correlation is a strong argument for a collapsar origin of long-duration GRBs.

Subject headings: gamma rays: bursts — stars: supernovae—cosmology:observations

1. Introduction

One can understand the dynamics of GRB afterglows simply, independent of uncertainties about their progenitors, using the relativistic generalization of the theory of supernova remnants. The basic model for GRB hydrodynamics is of a relativistic blast wave that expands into the surrounding interstellar medium (ISM; Mészáros & Rees 1997), decelerates on contact with the ambient matter, and leads to a predictable radiative spectrum with a characteristic power-law decline. The study of GRB afterglows has provided confirmation of relativistic source expansion (Piran 1999; Mészáros 2001). The energy source of the fireball is assumed to be a cataclysmic event, either a compact stellar merger (Lattimer & Schramm 1976; Eichler et al. 1989) or the collapse of a massive star (Woosley 1993; Paczynski 1998; MacFadyen & Woosley 1999, hereafter MW99).

Evidence is accumulating that GRBs are intimately linked with the deaths of massive stars. For the long-burst afterglows localized so far, the host galaxies show signs of the ongoing star formation activity necessary for the presence of young, massive progenitor stars (Kulkarni et al. 1998;

Fruchter et al. 1999; Berger et al. 2001). The physical properties of the afterglows, their locations in host galaxies (Bloom, Kulkarni & Djorgovski 2001b), iron line features (Piro et al. 2000; Amati et al. 2000), and evidence for supernova components several weeks after three bursts (GRB980326, Bloom et al. 1999a; GRB970228, Reichart 1999; GRB 000911, Lazzati et al. 2001) strongly support the idea that the most common GRBs are linked to the collapse of massive stars.

The circumburst medium provides a natural laboratory for studying GRBs. Stars that readily shed their envelopes have short jet-crossing times and are more likely to produce a GRB. Stars with less radiative mass loss retain a hydrogen envelope, in which a poorly collimated jet is likely to lose energy and fail to breaking out of the star (MW99). Finding useful diagnostics for the progenitors is simplified if the metallicity of and physical conditions in the local ISM influences the evolution of the progenitor. GRBs occur close to the birth sites of their short-lived progenitors, and so their evolution is likely to be affected only by local properties of the host galaxy. Here, we show that bursts located closer to the center of their parent galaxies have smaller isotropic equivalent energies (or broader jets), and so progenitors in inner and outer galactic locations may be intrinsically different. We suggest that this could be the outcome of abundance gradients in the host galaxy. We assume $H_0 = 65\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_{\mathrm{matter}} = 0.3$, and $\Omega_\Lambda = 0.7$.

2. The offset of GRBs from their parental galaxies

Important information may be gained by studying the location of GRBs and host galaxies (Bloom et al. 1999b; 2001c). This approach was successful for studying SN progenitors even before detailed models of light-curves were available (e.g. Reaves 1953). Unfortunately this kind of observation is impossible for GRB host galaxies, as current instruments can only resolve circumburst environments with sizes of tens of parsecs at low redshifts $z \approx 0.1$, and so a physical understanding of the local GRB environment was thought to have to wait for *NGST*. Nonetheless, Bloom et al. (2001c) show that the distribution of the offsets of a small subset of GRBs with accurate positions from the centers of their host galaxies is an important probe of their progenitors. In our analysis, we consider all 16 bursts from Bloom et al. (2001c) with measured angular offsets, inferred physical projections, secure redshifts and K-corrected, isotropic equivalent burst energy estimates E_{iso} (Bloom, Frail & Sari 2001a), and also the recently imaged GRB 010222 (see Table 1). We searched for correlations between the normalized offsets of the bursts from the brightest component of their host system (r_0, offset/half-light radius) and their inferred physical properties, namely the external particle density and the isotropic equivalent energy of the jet. The discovery of a correlation could provide constraints on progenitor models. In particular, we investigated the dependence of E_{iso} on galactic location r_0. We found a marginally significant correlation, with the innermost bursts being least energetic (Fig. 1); a similar result is obtain using the measured physical projections, R_0 (see Table 1).

We fit a model for the correlation between $E_{\rm iso}$ and r_0 that takes into account the relative influence of each datum and its errors. We constructed the individual probability distribution $p_i(x,y)dxdy$ of the true offset at some distance x and y from the measured offset location (x_0, y_0), assuming that the errors in x and y are uncorrelated. The probability distribution should appear Gaussian when the offset is large, but clearly departs from a Gaussian form for small offsets, for which the ratio between the offset and its error is close to unity (see Fig. 10 of Bloom et al. 2001c). The distribution of bursts in the log r_0 – log $E_{\rm iso}$ plane can be well modeled by a normal distribution about a straight line (Fig. 1). To evaluate this correlation we created synthetic sets of observed data from the probability distributions of the measured values of both r_0 and $E_{\rm iso}$, assuming that the uncertainties in $E_{\rm iso}$ are Gaussian distributed. We then determined model parameters and their uncertainties by fitting 10^3 synthetic sets of data from Monte-Carlo realizations. We find that the correlation extends for ≈ 3 orders of magnitude in $E_{\rm iso}$, and has a positive slope, m, with a probability $P(m < 0) \approx 3.2\sigma$. The best-fit model is shown in Fig. 1 as a solid line: $r_0 \propto E_{\rm iso}^{\approx 0.3^{+0.2}_{-0.1}}$. This positive correlation could result from abundance gradients in the host galaxies and so some intrinsic scatter is expected (see Section 3).

There are some necessary limitations to our approach: we used only a subset of moderate-redshift bursts with $R < 28$ optical host galaxies, and well-localized afterglows at optical and radio wavelengths. Both high-redshift ($z > 3$) and heavily dust-enshrouded host galaxies could be missing. More importantly, dimmer bursts in the outskirts of galaxies may be missed owing to the average decrease in density of the ISM, n, which will lead to a systematic reduction in the afterglow brightness. This effect may be very important, but the afterglow flux depends on density as $F_\nu \propto n^{1/2}$, and so large variations in n are required to have noticeable effects: densities in the 0.1 to 50 cm^{-3} range can accommodate the broadband emission of most afterglows (Panaitescu & Kumar 2001). Moreover, the densities derived for these bursts do not correlate with their location in the host galaxy. This could be due in part to the certainly diverse fractal structure expected in the ISM. On the other hand, it is possible that the afterglows of bursts close to the galactic center are more likely to suffer dust extinction than those in the outer parts: this effect may open up a scatter in the correlation, as a greater fraction of the luminosity function becomes visible near the edges of the galaxy. It is also important to note that both the assignment of a certain observed galaxy as the host of a GRB and the position of its center are uncertain. However, Bloom et al. (2001c) find that the probability of a chance association is small $< 10^{-4}$; in most cases, the apparent host has only one bright component which is assigned as its center.

Recently, it was suggested (Frail et al. 2001; Panaitescu & Kumar 2001; Piran et al. 2001) that the total energy output of GRBs is constant, and that a distribution of jet opening angles causes the apparent dispersion in $E_{\rm iso}$. This analysis assumes that the breaks observed in many GRB afterglow light-curves are due to a geometrical beam effect (Rhoads 1997) and not to either a transition to non-relativistic expansion (Huang, Dai & Lu 2000) or an environmental effect such as a sharp density gradient (Chevalier & Li 2000; Ramirez-Ruiz et al. 2001). If the energy output of GRBs is fixed, then our correlation may imply a link between jet opening angle and burst location.

3. Abundance gradients and the physics of GRB progenitors

An exciting recent development in observational cosmology has been the extension of studies of abundances from the local Universe to high redshifts. The dependence of metallicity on environment appears to be stronger than on the redshift of formation: galaxies selected using the same techniques have metallicities rather independent of redshift, and old stars are not necessarily metal-poor (Pettini 2001). Chemical abundances within different galaxies depend strongly on luminosity and environment (e.g. Vila-Costas & Edmunds 1992; Zaritsky, Kennicut & Huchra 1994; Henry & Worthey 1999; Pettini 2001). From the center to the outermost 10 kpc, metallicity typically decreases by a factor of ten. A comparable change in metallicity only occurs over a range of a factor of a thousand in luminosity (see Fig. 5 of Pettini 2001). This is a much greater range of luminosity than displayed by moderate-redshift GRB host galaxies, which usually have magnitudes $R \approx 25$ (Table 1). These host galaxies are UV-bright (Trentham, Ramirez-Ruiz & Blain 2001), and so may exhibit comparable abundance gradients to their local counterparts. Drawing inferences about GRB hosts from local galaxies is difficult, however, since both merging and secular evolution are likely to be important and will complicate a direct comparison. Nonetheless, a direct association between abundance gradients in GRB hosts and in local galaxies could be responsible for the correlation presented in Fig. 1.

Low-metallicity stars, which are likely to be more prominent in the outskirts of the galaxy, are smaller and have less mass loss than their metal-rich counterparts. Both properties inhibit the loss of angular momentum (MW99), and so low-metallicity stars are likely to be rotating rapidly. Equatorial accretion may thus be delayed and a funnel may be produced along the rotation axis. For higher rotational velocities this evacuated region will be more collimated, reducing the jet opening angle. Furthermore, for a given mass-loss rate, the lower the metallicity, the higher both the WR stellar mass, and the mass threshold for the removal of the hydrogen envelope by stellar winds. These effects all increase the mass of the helium core and favor black hole formation (MW99, Ramirez-Ruiz et al. 2001). If there are abundance gradients in the hosts, then the likely metallicity dependence of both black-hole formation and rotation suggests that GRBs in outer galactic locations may be more energetic (greater helium core mass) or less collimated (faster rotation) than those close to the galactic center. In the local Universe, regular galaxies are found to have steeper abundance gradients than those with complex morphologies (Zaritsky et al. 1994). Indeed, it is reassuring that the most regular GRB host galaxies (shown as open circles in Fig. 1) firmly support the trend between $E_{\rm iso}$ and r_0. Note that the scatter in Fig. 1 can be due to the dependence of metallicity on luminosity. A more detailed analysis of the underlying reasons for the correlation requires a large and unbiased sample of GRBs hosts, and knowledge of both the underlying GRB and afterglow luminosity functions.

4. Consequences of a dependence of GRB properties on local metallicity

What are the potential effects of a significant dependence of GRB luminosity, as detected by unextinguished γ-ray photons, on their location in the host galaxy, which could reflect the metallicity of their progenitors? The most significant is a potential offset between the true star-formation rate and that traced by GRB. If GRBs in outlying, low-metallicity environments and in low-mass galaxies are more luminous, then they are likely to be overrepresented in GRB samples, and especially in the bright BATSE catalog, as compared with those in high-metallicity environments.

The radial dependence of metallicity Z in low-redshift spiral (Zaritsky et al. 1994) and elliptical galaxies (Henry & Worthey 1999), is $Z \propto \exp(-1.9R/\overline{R})$, while the dependence of metallicity at fixed radius on enclosed mass $M_{\rm enc}$ in spiral galaxies derived from Fig. 4 of Henry & Worthey is $Z \propto M_{\rm enc}^{\simeq -0.5}$. These functions both depend strongly on radius. Therefore, it is likely that local environmental effects will overcome global enrichment effects (Pettini et al. 2001), but that there will be a gradual increase in the typical luminosity of GRBs with increasing redshift (see Lloyd-Ronning, Fryer & Ramirez-Ruiz 2001).

Low-mass galaxies are likely to have statistically lower metallicities and thus contain more luminous GRBs than high-mass galaxies. As galaxy mass is expected to build up monotonically through mergers, then it is possible that the highest-redshift GRBs could be systematically more luminous due to the lower mass of their hosts, perhaps by a factor of 2–3 at $z \simeq 3$. This effect is likely to be more significant than, but in the same direction as, the global increase in metallicity with cosmic time.

The most luminous GRBs of all could be associated with metal-free Population-III stars; however, their very high redshifts would make examples difficult to find even in the *Swift* catalog of hundreds of bursts.

Star-formation activity is likely to be enhanced in merging galaxies. In major mergers of gas-rich spiral galaxies, this enhancement takes place primarily in the inner kpc, as bar instabilities drive gas into the core (Mihos & Hernquist 1994). Metallicity gradients in the gas are likely to be smoothed out, both by mixing prior to star formation, and by SN enrichment during the burst of activity. GRB luminosities could thus be suppressed in such well-mixed galaxies, making GRBs more difficult to detect in these most luminous objects, in which a significant fraction of all high-redshift star formation is likely to have occurred. Shocks in tidal tails associated with merging galaxies are also likely to precipitate the formation of high-mass stars, yet as tidal tails are likely to consist of relatively low-metallicity gas, it is perhaps these less intense sites of star-formation at large distances from galactic radii that are more likely to yield detectable GRBs.

For star formation taking place in both merging and quiescent high-redshift galaxies, there should thus be a bias in favor of detecting GRBs at a greater projected distance from the host galaxy than the mean radius of the star-formation activity. Hence, based on the correlation shown in Fig. 1, we predict that the radial distribution of a large sample of GRBs around their host galaxies should be considerably more extended than the signatures of star-formation regions within the host, such as blue colors, location of Hα emission, intense radio emission etc. This might have the unfortunate consequence of making GRBs more difficult to use as clean markers of high-redshift star-formation activity. Detailed observations of the astrophysics of individual GRB host galaxies may be essential before a large sample of bursts can be interpreted. More optimistically, the astrophysics of star formation in high-redshift galaxies could perhaps be studied using the intrinsic properties of a well-selected population of GRB with deep, resolved host galaxy images.

If confirmed in detailed studies, a metallicity selection effect for GRBs may be able to explain the differences between the star-formation rate infered from observations of galaxies (Steidel et al. 1999; Blain et al. 1999), which tend not to increase with redshift beyond $z \simeq 2$, and the rate inferred from GRB counts assuming a variability–luminosity relation (Fenimore & Ramirez-Ruiz 2001; Lloyd-Ronning et al. 2001), which continues to increase to the highest redshifts. This increase may reflect a bias to detecting high-redshift GRBs in more numerous, low-mass, low-metallicity high-redshift galaxies.

Another test of the effect could be provided by a comparison of the luminosity function of GRB host galaxies with that of the total galaxy luminosity function over the same redshift range. If there is a bias towards the discovery of GRBs in low-metallicity regions, then the GRB host galaxy luminosity function should be biased to low luminosities by an increasing amount as red-shift increases.

5. Conclusion

We report a correlation between the isotropic equivalent energy of GRBs and their position offset from their host galaxies. This is possibly due to a dependence of the end point of massive stellar evolution on metallicity. If confirmed in further host observations, this correlation will both complicate interpretation of GRBs as tracers of cosmic star formation, and potentially allow a new probe of the astrophysics in high-redshift galaxies.

We thank G. Denicoló, N. Lloyd-Ronning, M. Pettini, M. J. Rees, C. Tout and the referee for useful comments and suggestions. ERR acknowledges support from CONACYT, SEP and the ORS foundation. AWB thanks the Raymond & Beverly Sackler Foundation for financial support at the IoA.

REFERENCES

Amati, L., et al. 2000, Science, 290, 953

Berger E., Kulkarni S. R., Frail D. A., 2001, ApJ, 560, 652

Blain, A. W., Smail, I., Ivison, R. J., Kneib, J.-P., 1999, MNRAS, 302, 632

Bloom J. S. et al. 1999b, MNRAS, 305, 763

Bloom J. S. et al. 1999a, Nature, 401, 453

Bloom J. S., Frail, D. A. & Sari R. 2001a, AJ, 121, 2879

Bloom, J. S., Kulkarni S. R. & Djorgovski, S. G. 2001b, ApJ, 554, 678

Bloom, J. S., Kulkarni S. R. & Djorgovski, S. G. 2001c, Apj submitted (astro-ph/0010176)

Chevalier R. A., Li Z.-Y., 2000, ApJ, 536, 195

Djorgovski S. G., et al., 2001, in Gurzadyan V., Jantzen R., Ruffini R., eds, Proc. IX Marcel Grossmann Meeting, World Scientific, Singapore, in press (astro-ph/0106574)

Eichler, D., Livio, M., Piran, T., Schramm, D. N 1989, Nature, 340, 126

Fenimore, E. E. & Ramirez-Ruiz, E. 2001, ApJ, submitted (astro-ph/0004176)

Frail, D. A. et al. 2001, ApJ, 562, L55

Fruchter A. S. et al. 1999, ApJ, 520, 54

Fruchter A. S. et al. 2001, GCN 1087.

Henry R. B. C., Worthey G., 1999, PASP, 111, 919

Huang, Y. F., Dai, Z. G., & Lu, T. 2000, MNRAS, 316, 943

Kulkarni S. R. et al. 1998, Nature, 395, 663

Lattimer, J. M. & Schramm, D. N. 1976, ApJ, 210, 549

Lazzati et al. 2001, A&A, 378, 996

Lloyd-Ronning, N. M., Fryer, C. L. & Ramirez-Ruiz, E. 2001, ApJ, submitted (astro-ph/0108200)

MacFadyen, A. I. & Woosley, S. E. 1999, ApJ, 524, 262 (MW99)

Mészáros, P. & Rees, M. J. 1997, ApJ, 476, 232

Mészáros, P. 2001 Sci, 291, 79

Mihos, J. C. & Hernquist, L. 1994, 431, L9

Paczyński B. 1998, ApJ, 494, L45

Panaitescu, A. & Kumar, P. 2001, ApJ, 560, L49.

Pettini, M. 2001, Proc. of the 'The promise of First', Pilbratt, Cernicharo, Heras & Prusti eds., ESA SP-460.

Piran, T. 1999, Physics Reports, 314, 575

Piran, T., Kumar, P., Panaitescu, A. & Piro, L. 2001, ApJ, 560, L167

Piro, L. et al., 2000, Science, 290, 955

Ramirez-Ruiz, E., Dray, L., Madau, P., Tout, C. A. 2000, MNRAS, 327, 829

Reaves, G. 1953, PASP, 65, 242

Reichart D. E. 1999, ApJ, 521, L111

Rhoads, J. E. 1997, ApJ, 487, L1

Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., Pettini, M. 1999, ApJ, 519, 1

Trentham, N., Ramirez-Ruiz, E. & Blain, A. W. 2001, MNRAS submitted

Vila-Costas, M. B. & Edmunds, M. G. 1992, MNRAS, 259, 121

Woosley, S. E., 1993 ApJ, 405, 273

Zaritsky, D., Kennicut, R. C. & Huchra J. P. 1994, ApJ, 420, 87

This preprint was prepared with the AAS LaTeX macros v5.0.

Table 1: Properties of GRBs and host galaxies with known redshifts

Burst	z	$E_{\rm iso}^{\rm a}$ (10^{51}erg)	$R_0^{\rm b}$ (kpc)	$r_0^{\rm b}$	Host R mag[c]
970228	0.695	22.4 ± 2.50	3.266 ± 0.259	1.37 ± 0.25	24.6
970508	0.835	6.33 ± 0.82	0.09 ± 0.09	0.03 ± 0.03	25.8
970828	0.958	249 ± 21.7	4.05 ± 4.33	1.63 ± 1.80	24.5
971214	3.418	185 ± 51.6	1.1 ± 0.56	0.43 ± 0.23	25.6
980613	1.100	5.67 ± 1.0	0.78 ± 0.67	1.37 ± 1.57	26.1
980703	0.966	121 ± 16.0	0.96 ± 0.54	0.62 ± 0.39	22.8
990123	1.600	3280 ± 512	6.11 ± 0.03	2.09 ± 0.63	23.9
990506	1.300	874 ± 144	2.680 ± 4.144	2.47 ± 3.96	25.0
990510	1.619	168 ± 27.1	0.60 ± 0.08	0.44 ± 0.15	28.5
990705	0.850	270 ± 20.2	7.17 ± 0.78	0.79 ± 0.06	22.8
990712	0.433	5.27 ± 0.67	0.30 ± 0.49	0.20 ± 0.32	24.4
991208	0.706	147 ± 19.8	1.51 ± 0.75	0.60 ± 0.35	24.4
991216	1.020	564 ± 79.3	3.11 ± 0.28	1.27 ± 0.40	24.9
000301C	2.033	46.4 ± 6.2	0.62 ± 0.06	0.44 ± 0.14	27.8
000418	1.119	297 ± 99.0	0.20 ± 0.56	0.07 ± 0.19	23.9
010222	1.476	712 ± 83.0	1.23 ± 1.30	0.79 ± 0.83	>24.0

[a]The isotropic, K-corrected, equivalent energies (20-2000 keV; Bloom et al. 2001a).
[b]The projected physical offset R_0 and the host normalized offset (offset/half-light radius) r_0 are taken from Bloom et al. (2001c). The values for GRB 010222 are derived from Fruchter et al. (2001). The associated uncertainties in the observed offsets do not necessarily represent the 1σ confidence region of the true offset since the probability distribution is not Gaussian (Bloom et al. 2001c).
[c]Djorgovski et al. (2001) and Trentham et al. (2001).

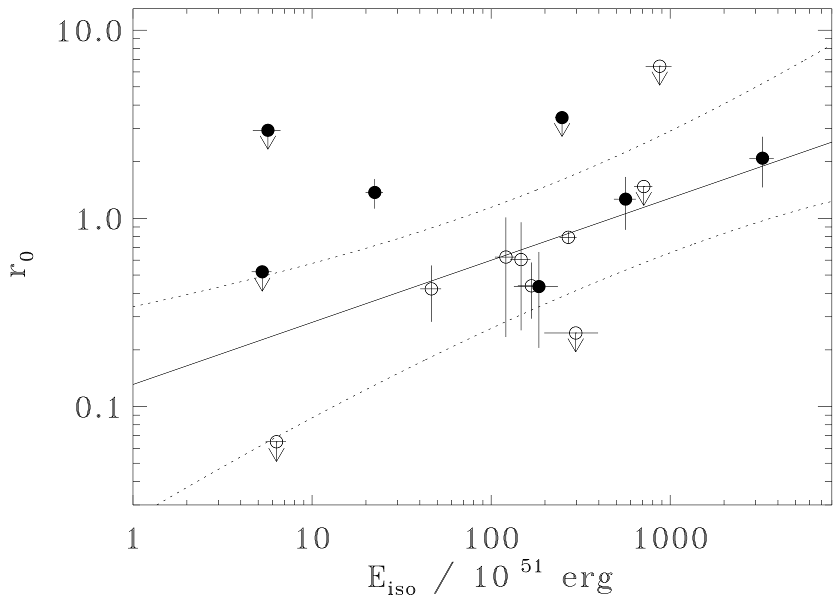

Fig. 1.— The projected observed offset of GRBs from their parental galaxy as a function of the burst isotropic equivalent energy. The center of the assigned host is determined as the centroid of the brightest component of the host system. The fractional isophotal offsets are the observed offsets R_0 normalized by the host half-light radius. Solid and dotted lines mark the center and 1σ widths of the best-fit model distributions parameters. The filled circles are bursts that occur in the most irregular, possibly merging galaxies, while the empty circles are bursts with more regular hosts. There is a tentative trend: the inner most bursts seem to be less energetic (similar trend is obtained when the projected physical offsets in kpc are plotted against the equivalent isotropic energy).